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Specification and Drawings, as originally filed, with Application for Patent Serial No: **2,324,702**, on October 27, 2000, by **QUESTAIR TECHNOLOGIES INC.**, assignee of Bowie Keefer, Erik Johannes and Denis Connor, for "Reformate Purification and Heat Recovery for Fuel Cell".
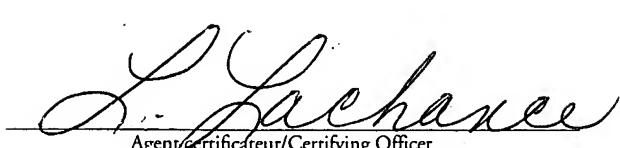
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REFORMATE PURIFICATION AND HEAT RECOVERY FOR FUEL CELL

FIELD OF THE INVENTION

The present invention relates to a fuel cell-based electrical generation system which employs pressure swing adsorption for enhancing the efficiency and durability of the fuel cell.

BACKGROUND OF THE INVENTION

Fuel cells provide an environmentally friendly source of electrical current. One form of fuel cell used for generating electrical power, particularly for vehicle propulsion and for smaller scale stationary power generation, includes an anode channel for receiving a flow of hydrogen gas, a cathode channel for receiving a flow of oxygen gas, and a polymer electrolyte membrane (PEM) which separates the anode channel from the cathode channel. Oxygen gas which enters the cathode reacts with hydrogen ions which cross the electrolyte to generate a flow of electrons. Environmentally safe water vapour is also produced as a byproduct.

External production, purification, dispensing and storage of hydrogen (either as compressed gas or cryogenic liquid) requires costly infrastructure, while storage of hydrogen fuel on vehicles presents considerable technical and economic barriers. Accordingly, for stationary power generation, it is preferred to generate hydrogen from natural gas by steam reforming or partial oxidation followed by water gas shift. For fuel cell vehicles using a liquid fuel, it is preferred to generate hydrogen from methanol by steam reforming or from gasoline by partial oxidation or autothermal reforming, again followed by water gas shift. However, the resulting hydrogen contains carbon monoxide and carbon dioxide impurities which cannot be tolerated respectively by the PEM fuel cell catalytic electrodes in more than trace levels.

The conventional method of removing residual carbon monoxide from the hydrogen feed to PEM fuel cells has been catalytic selective oxidation, which compromises efficiency as both the carbon monoxide and a fraction of the hydrogen are consumed by low temperature oxidation, without any recovery of the heat of combustion. Palladium diffusion membranes can be used for hydrogen purification, but have the disadvantages of delivery of the purified hydrogen at low pressure, and also the use of rare and costly materials.

Pressure swing adsorption systems (PSA) have the attractive features of being able to provide continuous sources of oxygen and hydrogen gas, without significant contaminant levels. PSA systems and vacuum pressure swing adsorption systems (VPSA) separate gas fractions from a gas mixture by coordinating pressure cycling and flow reversals over an adsorber or adsorbent bed which preferentially adsorbs a more readily adsorbed gas component relative to a less readily adsorbed gas component of the mixture. The total pressure of the gas mixture in the adsorber is elevated while the gas mixture is flowing through the adsorber from a first end to a second end thereof, and is reduced while the gas mixture is flowing through the adsorbent from the second end back to the first end. As the PSA cycle is repeated, the less readily adsorbed component is concentrated adjacent the second end of the adsorber, while the more readily adsorbed component is concentrated adjacent the first end of the adsorber. As a result, a "light" product (a gas fraction depleted in the more readily adsorbed component and enriched in the less readily adsorbed component) is delivered from the second end of the adsorber, and a "heavy" product (a gas fraction enriched in the more strongly adsorbed component) is exhausted from the first end of the adsorber.

However, the conventional system for implementing pressure swing adsorption or vacuum pressure swing adsorption uses two or more stationary adsorbers in parallel, with directional valving at each end of each adsorber to connect the adsorbers in alternating sequence to pressure sources and sinks. This system is often cumbersome and expensive to implement due to the large size of

the adsorbers and the complexity of the valving required. Further, the conventional PSA system makes inefficient use of applied energy because of irreversible gas expansion steps as adsorbers are cyclically pressurized and depressurized within the PSA process. Conventional PSA systems could not be

5   applied to fuel cell power plants for vehicles, as such PSA systems are far too bulky and heavy because of their low cycle frequency and consequently large adsorbent inventory.

     Another problem is the need for air compression with a substantial

10   mechanical parasitic load to achieve high power density and high voltage efficiency with PEM fuel cells, either in the absence of PSA in prior art fuel cell systems, or to a lesser extent with the use of PSA to increase oxygen concentration. If as usual that mechanical power is provided by a electric motor powered by the fuel cell, significant efficiency losses are entailed in electrical

15   power conversion and conditioning for variable speed compressor drive, and the fuel stack must be substantially larger to support this parasitic load as well as the application load to which useful power is delivered. In prior art PEM fuel cell power plants for automotive and other transportation applications, approximately 20% of fuel cell gross power output is diverted to the parasitic load of air

20   compression.

     Yet another problem arises in the need to provide heat for endothermic fuel processing reactions to generate low purity reformate hydrogen from hydrocarbon fuels (e.g. natural gas, gasoline or diesel fuel) or oxygenate fuels (e.g. methanol,

25   ethanol or dimethyl ether). In the prior art, the necessary heat is provided for steam reforming of natural gas or methanol at least in part by burning hydrogen provided as anode tail gas from the fuel cell. Especially in the case of methanol reforming which can be performed at relatively low temperature, combustion of valuable hydrogen to generate such low grade heat is extremely detrimental to

30   overall exergetic efficiency.

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Likewise, the necessary heat for processing of heavier fuels such as gasoline is achieved by combustion of a portion of the fuel in a partial oxidation or autothermal reforming process. Again, a portion of the high grade fuel is consumed to upgrade the remainder of that fuel to low purity hydrogen than can

5   be purified for use in the fuel cell. With a low temperature fuel cell, thermal efficiency of prior art fuel processing systems has been extremely low, as high grade fuel is consumed. No opportunity has been found for efficient thermal integration between a high temperature fuel processor and a low temperature fuel cell in transport applications.

10

SUMMARY OF THE INVENTION

According to the invention, there is provided a fuel cell based electrical generation system which addresses the deficiencies of the prior art fuel cell

15   electrical generation systems, particularly as to energy-efficient PSA oxygen enrichment, PSA purification of reformate hydrogen, heat recovery form the fuel cell stack and/or from combustion of hydrogen PSA tail gas, and thermal powering of air compression for the oxygen PSA and of any PSA vacuum pumping so as to minimize the size of the costly fuel cell stack while maximizing

20   overall exergetic efficiency of energy conversion from the raw fuel.

The electrical current generating system comprises a fuel cell, an oxygen gas delivery system, and a hydrogen gas delivery system. The fuel cell includes an anode channel having an anode gas inlet for receiving a supply of hydrogen

25   gas, a cathode channel having a cathode gas inlet and a cathode gas outlet, and an electrolyte in communication with the anode and cathode channel for facilitating ion transport between the anode and cathode channel. The oxygen gas delivery system is coupled to the cathode gas inlet and delivers air or oxygen (e.g. oxygen enriched air) to the cathode channel.

30

The oxygen gas delivery system may simply be a air blower. However, for superior performance it incorporates an oxygen pressure swing adsorption

system, including a rotary module having a stator and a rotor rotatable relative to the stator, for enriching oxygen gas from air. The rotor includes a number of flow paths for receiving adsorbent material therein for preferentially adsorbing a first gas component in response to increasing pressure in the flow paths relative to

5   a second gas component. The pressure swing adsorption system also may include compression machinery coupled to the rotary module for facilitating gas flow through the flow paths for separating the first gas component from the second gas component. The stator includes a first stator valve surface, a second stator valve surface, and plurality of function compartments opening into the stator valve

10   surfaces. The function compartments include a gas feed compartment, a light reflux exit compartment and a light reflux return compartment.

In one variation, the compression machinery comprises a compressor for delivering pressurized air to the gas feed compartment, and a light reflux expander

15   coupled between the light reflux exit compartment and the light reflux return compartment. The gas recirculating means comprises a compressor coupled to the light reflux expander for supplying oxygen gas, exhausted from the cathode gas outlet, under pressure to the cathode gas inlet. As a result, energy recovered from the pressure swing adsorption system can be applied to boost the pressure of

20   oxygen gas delivered to the cathode gas inlet.

The oxygen gas delivery system is coupled to the cathode gas inlet and delivers oxygen gas to the cathode channel. The hydrogen gas delivery system supplies purified hydrogen gas to the anode gas inlet, and may have provision for

25   recirculating hydrogen gas from the anode gas exit back to the anode gas inlet with increased purity so as to avoid accumulation of impurities in the anode channel.

In a preferred embodiment, the oxygen gas separation system comprises an oxygen pressure swing adsorption system, and the hydrogen gas separation system

30   comprises a reactor for producing a first hydrogen gas feed from hydrocarbon fuel, and a hydrogen pressure swing adsorption system coupled to the reactor for purifying hydrogen gas received from the first hydrogen gas feed. Hydrogen gas

from the anode exit may be recirculated to the hydrogen pressure swing adsorption system as a second hydrogen gas feed for a feed repressurization step of the PSA cycle. Both pressure swing adsorption systems include a rotary module having a stator and a rotor rotatable relative to the stator. The rotor includes a number of

5   flow paths for receiving adsorbent material therein for preferentially adsorbing a first gas component in response to increasing pressure in the flow paths relative to a second gas component. The function compartments include a gas feed compartment and a heavy product compartment.

10   The feed gas to the hydrogen PSA system is reformate gas or "syngas", generated in alternative fuel processing methods known to the art by steam reforming (e.g. of methanol or natural gas or light hydrocarbons), or by autothermal reforming or partial oxidation (e.g. of natural gas, gasoline or diesel fuel). The CO content of methanol reformate (generated by relatively low

15   temperature steam reforming of methanol) is typically about 1%. Other fuel processors (e.g. steam methane reformers, and POX or autothermal reformers operating on any feedstock) operate at much higher temperature, and preferably include a lower temperature water gas shift reactor stage to reduce to CO content to about 1%.

20

The reformate gas contains hydrogen plus the basic impurity components of CO_2, CO and water vapour. If generated by air-blown POX or autothermal reforming, the reformate gas will also contain a large inert fraction of nitrogen and argon. The fraction of inert atmospheric gases can be greatly reduced if an

25   oxygen PSA system is used to supply the POX or autothermal reformer, either directly from the PSA, or as humid and still oxygen enriched air that has been passed through the fuel cell cathode channel which was directly fed oxygen-enriched air from the PSA.

30   In one variation, the oxygen pressure swing adsorption system includes a compressor coupled to the gas feed compartment for delivering pressurized air to the gas feed compartment, and a vacuum pump coupled to the compressor for

extracting nitrogen product gas from the heavy product compartment. The reactor comprises a steam reformer, including a burner, for producing syngas, and a water gas shift reactor coupled to the steam reformer for converting some CO to hydrogen. The hydrogen pressure swing adsorption system includes a vacuum pump for delivering fuel gas from the heavy product compartment to the burner. The fuel gas is burned in the burner, and the heat generated therefrom is used to supply the endothermic heat of reaction necessary for the steam reformer reaction. The resulting reformate gas is delivered to the water gas shift reactor for removal of impurities, and then delivered as the impure hydrogen gas feed to the hydrogen pressure swing adsorption system.

In another variation, the invention includes a burner for burning fuel. The reactor comprises an autothermal reformer for producing syngas, and a water gas shift reactor coupled to the autothermal reformer for converting the syngas to the second hydrogen gas feed. The compressor of the oxygen pressure swing adsorption system delivers pressurized air to the burner, and the heavy product gas is delivered from the hydrogen pressure swing adsorption system as tail gas to be burned in the burner. The compression machine of the oxygen pressure swing adsorption system also includes an expander coupled to the feed compressor for driving the compressor from hot gas of combustion emitted from the burner. The feed compressor with the expander may be on a common shaft with a motor drive, or may constitute a free rotor similar to an automotive turbocharger. The same expander or another expander may be coupled to a vacuum pump to assist the PSA process. Again, the vacuum pump with its expander may be provided as a free rotor similar to an automotive turbocharger. Heat from the burner may also be applied to preheat air and/or fuel supplied to the autothermal reformer.

Independently of whether PSA is used for oxygen enrichment, the present invention provides a hydrogen PSA apparatus for purifying the reformate. The hydrogen PSA may be designed to deliver high purity hydrogen, or else may be designed less stringently to achieve adequately high removal of noxious components (harmful to the fuel cell) such as CO, H2S, halogens, methanol, etc.

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In the latter case, the hydrogen PSA would in its first pass only achieve partial removal of less harmful constituents (e.g., N2, Ar and CO2).   In that case, anode tail gas would then preferably be recycled to the feed end of the PSA inlet for use in a feed pressurization step, thus avoiding any need for mechanical

5   recompression.   Even when high hydrogen purity is specified for the PSA, this feature enables a small bleed from the end of the anode channel back to the feed pressurization step of the hydrogen PSA, as would be desirable for avoiding a strict dead-headed configuration with the risk of accumulation in the anode channel of any contaminant slip due to equipment imperfections or operational transient

10   upsets.

Operating temperature of the adsorbers in the hydrogen PSA unit of the invention will preferably be elevated well above ambient, as the reformate gas is supplied at a temperature after water gas shift of typically about 200°C, while

15   operating temperatures of PEM fuel cells may extend from 80°C to about 100°C. Alternatively, the adsorbers may be operated at a lower temperature if the reformate is cooled, thus providing an opportunity for partial removal of water and any methanol vapour by condensation before admission to the hydrogen PSA unit. Advantages of operation at moderately elevated temperature are (1) reformate

20   coolers and water condensers upstream of the hydrogen PSA can be avoided, (2) PSA removal of water vapour and CO2 may be more readily achieved at moderately elevated temperature compared to ambient temperature, (3) CO can be more selectively adsorbed than CO2 over Cu(I) loaded adsorbents particularly at elevated temperature, and (4) kinetics of CO sorption and desorption on CO-

25   selective sorbents will be greatly enhanced at higher temperature.   Consequently a preferred operating temperature range for the adsorbers is from about 80°C to about 200°C, and a more preferred operating range is from about 100°C to about 160°C.

30   The hydrogen PSA unit may be configured to support a temperature gradient along the length of the flow channels, so that the temperature at the first

end of the adsorbers is higher than the temperature at the second end of the adsorbers.

Especially in the mode of design for low purity hydrogen with anode recycle, the hydrogen PSA may use CO-selective adsorbents with CO-complexing ions Cu(I) or Ag introduced by ion exchange or impregnation into a suitable adsorbent carrier. Prior art CO-selective adsorbents have used a wide diversity of zeolites, alumina or activated carbon adsorbents as carriers. With CO-selective adsorbents, enhanced hydrogen recovery may be achieved while tolerating some accumulation of non-CO impurities circulated through the fuel cell anode loop.

In the present invention, the active adsorbent preferably including a CO-selective component is supported on thin adsorbent sheets which are layered and spaced apart by spacers defining flow channels, so as to provide a high surface area parallel passage support with minimal mass transfer resistance and flow channel pressure drop. With crystalline adsorbents such as zeolites, and amorphous adsorbents such as alumina gel or silica gel, the adsorbent sheet is formed by coating or in-situ synthesis of the adsorbent on a reinforcement sheet of inert material, e.g. a wire mesh, a metal foil, a glass or mineral fiber paper, or a woven or nonwoven fabric. Active carbon adsorbent may also be coated onto a reinforcement sheet of inert material, but adosrbent sheets of active carbon may also be provided as self-supporting carbon fiber paper or cloth. Adsorbers of the layered adsorbent sheet material may be formed by stacking flat or curved sheets; or by forming a spiral roll, with the flow channels between the sheets extending from the first end of the adsorber to the second end thereof; to fill the volume of the adsorber housing of the desired shape. Typical thickness of the adsorbent sheet may be in the range of about 100 to about 200 microns, while flow channel spacing between the sheets may be in the range of about 50 to about 200 microns.

In the present invention, the adsorbent material contacting the flow channels between the first and second ends of the adsorbers may in general be selected to be different in distinct zones of the flow channels, so that the

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adsorbers would have a succession of zones (e.g. a first zone, a second zone, a third zone, a perhaps additional zones) with distinct adsorbents proceeding along the flow channels from the first end to the second end.

5   In a first variant configured to deliver high purity hydrogen, the adsorbent in a first zone of the adsorbers adjacent the first end will be a dessicant to achieve bulk removal of water vapour in that first zone, the adsorbent in a second zone in the central portion of the adsorbers will be selected to achieve bulk removal of CO_2 and some removal of CO, and the adsorbent in a third zone of the adsorbers

10   will be selected to achieve final removal of CO and substantial removal of any nitrogen and argon. A suitable dessicant for the first zone is alumina gel. A suitable adsorbent for the second zone is 13X zeolite, or 5A, or active charcoal. Suitable adsorbents for the third zone may be a strongly carbon monoxide and nitrogen selective adsorbent selected from the group including but not limited to

15   Na-LSX, Ca-LSX, Li-LSX, Li- exchanged chabazite, Ca- exchanged chabazite, Sr- exchanged chabazite. The zeolite adsorbents of this group are characterized by strong hydrophilicity, corresponding to selectivity for polar molecules. This first variant relying on physical adsorption will operate most effectively at relatively lower temperatures, unlikely to exceed much more than about 100°C

20   although certain adsorbents such as Ca- or Sr-exchanged chabazite would remain adequately effective for CO and N2 removal at temperatures to about 150°C. The adsorbent in the second or third zone may be a more strongly carbon monoxide selective adsorbent such as a Cu(I)-exchanged zeolite such as an X or a Y zeolite, mordenite, or chabazite.   Alternatively, the adsorbent in some or all zones of

25   the adsorbers may be a hydrophobic adsorbent selected from the group including but not limited to active carbon, Y-zeolite and silicalite; and preferably containing Cu(I) for enhanced CO- selectivity in a zone adjacent the second end of the adsorbers.
tivity.

30

        In another variant configured to deliver at least partially purified hydrogen with CO nearly completely removed, the adsorbent in the first or second zone of

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the adsorbers will include a component catalytically active at the operating temperature of that zone for the water gas shift reaction. A portion of the carbon monoxide sorbed onto the catalytically active component may then react with water vapour by the water gas shift reaction to generate carbon dioxide and
5   additional hydrogen.

Industrial H2 PSA is normally conducted at considerably elevated pressures (> 10 bara) to achieve simultaneous high purity and high recovery ($\sim$ 80% - 85%). Fuel cell systems operating with pressurized methanol reformers or in
10   integration with gas turbine cycles may operate at relatively high pressures. However, most PEM fuel cell systems operate at ambient to about 3 bara pressure. As feed pressure and the overall working pressure ratio of the PSA are reduced, productivity and recovery of a simple cycle deteriorate. Under given pressure conditions, use of CO-selective adsorbents should significantly improve recovery
15   at specified product CO concentration, if hydrogen purity with respect to other impurities such as nitrogen and carbon dioxide can be relaxed.

At very low feed pressures (e.g. 2 - 3 bara), the H2 PSA would need supplemental compression to achieve high recovery. We may consider vacuum
20   pumping to widen the working pressure ratio, or alternatively "heavy reflux" which is recompression and recycle to the PSA feed of a fraction of its exhaust stream at full pressure. Vacuum and heavy reflux options may be combined in PSA systems for reformate purification. We have successfully used the heavy reflux option, without CO-selective adsorbents or any vacuum pumping, in a lab
25   bench PSA device to achieve $\sim$ 95% recovery from synthetic methanol reformate at $\sim$ 3 bara feed pressure.

To get heavy reflux in a very low pressure PSA, the vacuum pump may be configured so that part of its flow is reinjected into the PSA feed. Extremely
30   high hydrogen recovery can then be obtained (even at a fairly low overall pressure ratio) just by pumping enough heavy reflux. The vacuum level can be traded against the mass flow of heavy reflux.

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A fuel cell may be a stand-alone power plant, or else it may be integrated with some type of combustion engine. In the case of a stand-alone fuel cell, all mechanical power for air handling compression and any oxygen and/or hydrogen PSA units must be provided as electrical power by the appropriately sized fuel cell

5   stack. In this case, tight constraints apply to the recovery level that must be achieved by the H_2 PSA at specified purity. In the absence of any useful export use for high grade heat, an efficient heat balance requires that the heating value of combustible waste gases (H_2, CO and unreacted fuel) be matched to the heat demand of the fuel processor. For a fuel cell with steam reforming (e.g. methanol

10   or natural gas), nominal hydrogen recovery by the H_2 PSA has to be about 75% to 80% as the PSA tail gas is burned to heat the reformer; while for a POX or autothermal reformer, hydrogen recovery by the PSA needs to be extremely high (at least 90% to 95%) as such reformers can only use a limited amount of external combustion heat from burning PSA tail gas or fuel cell anode tail gas, e.g. for

15   preheating feed oxygen/air and fuel reactants to the reformer.

Also to be considered are combined cycles where a combustion engine is integrated with a fuel cell. Here, the above strict heat balance constraints on necessary hydrogen recovery to be achieved by the PSA may be relaxed in

20   designing for most desirable technical, emissions and economic performance of the power plant. The prior art includes combined cycle power plants with a gas turbine cycle integrated with a fuel cell system. Fuel cell auxiliary power units have been proposed for automobiles and passenger railcars with internal combustion engines as primary power plants.

25

Co-pending Canadian patent application No. 2,274,240 provides examples of how PSA units may be integrated with gas turbine power plants, or with fuel cell power plants having a gas turbine auxiliary engine. The gas turbine may power all compressors and vacuum pumps for the O2 PSA, along with vacuum

30   pump and/or heavy reflux compression for the H2 PSA. This auxiliary gas turbine cycle allows a heavy reflux vacuum pump and compressor to be driven by the turboexpander which expands the products of hydrogen PSA tail gas

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combustion.   A feature here is integration of the vacuum pump(s) with the gas turbine powered by tail gas combustion. Either single or multiple spool gas turbine configurations may be considered. Centrifugal or axial machines may be used as the compressors and pumps. Approaches based on integration of gas

5   turbines and fuel cells are particularly favourable for larger power levels.

In order to achieve high process efficiency and high recovery of the PSA units along with high overall efficiency of the fuel cell system, the hydrogen PSA tail gas may be burned in an auxiliary combustion engine to drive the air handling

10   system compressor and any vacuum pumps for the oxygen and hydrogen PSA units. For smaller plants, internal combustion engines may be attractive relative to gas turbine configurations.   Either way, powering the compressor and vacuum pump(s) by burning tail gas avoids the cost penalty of a bigger fuel cell stack in order to run compression machinery as parasitic electrical loads.   The engine

15   exhaust heat and/or cooling jacket heat may be further recovered to preheat and vaporize fuel reactants and to provide some or all of the heat of reforming for a methanol reformer.

The engine could be a reciprocator or a rotary engine.   It may aspirate the

20   hydrogen PSA tail gas directly as fuel, or else be turbocharged to pull greater vacuum from the PSA exhaust. Modern Wankel derivative engines have favourable specific displacement and power density. Thus an auxiliary internal combustion engine could act as its own vacuum pump on tail gas being inducted directly as fuel. Some oxygen enriched tail gas from the fuel cell cathode could

25   be fed as a supplement to intake air to make up for the heavy load of CO2. In view of the hydrogen, water and carbon dioxide content of the tail gas fueling this engine, conditions are favourable for extremely low emissions of NOx and other noxious contaminants.

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Heat Recovery Methanol Reformer System for Low Pressure Fuel Cell

The conventional approach for methanol reforming is to pump the liquid
reactants to an elevated pressure for vaporization and the vapour phase methanol
5   reforming reaction. This approach enables the reactor itself to be compact, and
provides driving pressure for hydrogen purification by PSA or palladium diffusion
membranes.

A novel low pressure process for steam methanol reforming can get
10   enhanced heat recovery from a low pressure fuel cell. More than 60% of the
endothermic heat of steam reforming methanol is in fact the heat of vaporization to
boil the methanol and the water inputs. If the fuel cell is cooled to vaporize feed
liquid fuel and water at the fuel cell stack working temperature, the system could
be more efficient due to this heat recovery which liberates hydrogen to generate
15   electricity while absorbing about 25% of the stack cooling load. A water-rich mix
of 14% methanol in water will boil at atmospheric pressure and 85°C to generate a
50/50 vapour mix as required by stoichiometry, or at a modestly higher
temperature with a larger excess of water in the liquid phase to obtain a small
excess of steam as actually required to ensure low CO concentration. Therefore
20   the liquid mixture of water containing a fraction of methanol may be circulated as
fuel cell stack coolant, and then flash evaporated to generate a methanol-H2O
vapour mix to be admitted into the reforming catalyst chamber at fuel cell system
working pressure. If the fuel cell were operating at less than 85°C, flash
evaporation would have to be performed under vacuum or else with a higher
25   concentration of methanol (as also desirable for antifreeze characteristics for
winter conditions) so that only a fraction of the water required for methanol
reforming is provided by vaporization using fuel cell stack waste heat. As higher
PEM fuel cell operating temperatures are considered, this concept becomes more
viable as permitting either atmospheric or higher pressure for flash evaporation, or
30   else a larger temperature differential driving heat exchange in the stack coolant
channels.

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The above concept of stack heat recovery to boil the methanol reforming reactants is more attractive for a relatively low pressure fuel cell, unless the working temperature were greatly increased. If all the steam feed to the methanol reformer is generated by stack heat recovery, some mechanical compression of the reformer reactant vapour mixture would be needed except for a very low pressure PEM fuel cell (e.g. operating at a pressure below 1.5 bars absolute). Such a very low pressure fuel cell would be expected to benefit greatly from PSA O2 enrichment as enabling high power density at low total pressure. However, vacuum pumping would then be required for both the oxygen PSA and a hydrogen PSA unit, particularly to obtain high recovery of hydrogen in the hydrogen PSA.

An alternative approach within the invention is to operate the fuel cell at somewhat higher pressure (e.g. operating at a pressure of about 2 or 3 bars absolute), with the stack coolant liquid mixture of water and methanol containing a higher concentration of methanol, so that the vapour mixture thus generated contains all the methanol vapour for the methanol reformer, plus only a portion of the steam required for reforming that methanol. Supplementary steam is then generated by an alternative heat source, for example exhaust heat or cooling jacket heat from a combustion engine or turbine used to drive the feed air compressor and any vacuum pumps required to operate the PSA equipment.

In the case of a POX or autothermal gasoline fuel processor, the endothermic heat for the reforming reaction is generated by burning a portion of the fuel stream within the reforming reactor. Hence, there is at most a very limited opportunity for burning the hydrogen PSA tail gas usefully to support the reforming process (e.g. to preheat incoming air and fuel streams), because ample high grade heat is generated within POX and autothermal reformers. If there is no other use for combustion heat from burning the hydrogen PSA tail gas, it will be obvious that the hydrogen PSA would have to achieve extremely high hydrogen recovery (in the range of e.g. 90% to 99%) to achieve heat balance and full utilization of fuel. In the case of a methanol reformer with stack heat recovery to boil the reactants as provided above within the present invention, the hydrogen

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PSA would have to achieve very high hydrogen recovery ($\sim$ 90%) in view of the substantial heat recovery from the stack to reduce the methanol reformer heat demand.

5   The present invention therefore provides for an auxiliary combustion engine or turbine, cooperating with the fuel cell power plant to at least assist the feed air compression and any vacuum pumping loads. Tail gas from the hydrogen PSA unit is now usefully consumed as fuel for the auxiliary combustion engine or turbine, so that the necessary hydrogen recovery achieved by the PSA unit may be 10   relaxed to the range of e.g. 70% to 90% as the heat balance and fuel utilization constraints are opened. Hence, the need for heavy reflux compression and vacuum pumping to assist the hydrogen PSA unit is reduced or eliminated. Simultaneously, the auxiliary combustion engine or turbine unloads the PSA compression and any vacuum pumping load from the fuel cell electrical output, 15   thus reducing the size and cost of the fuel cell.

        The thermally integrated combination of the auxiliary combustion engine or turbine with the fuel processor provides alternative waste heat sources for vaporizing steam directly at the reforming pressure, for heating an endothermic 20   reactor, and for recovering exothermic heat e.g. of water gas shift. A thermally integrated design can also be configured to minimize thermal inefficiencies, e.g. of heat loss by conduction to the environment, simply by placing hot components of the fuel processsor and the auxiliary heat engine within a common housing, and with components at similar operating temperatures in close adjacent proximity.

25

BRIEF DESCRIPTION OF THE DRAWINGS

        Fig. 1 shows an axial section of a rotary PSA module.

30   Figs. 2 through 5B show transverse sections of the module of Fig. 1.

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Fig. 6 is a simplified schematic of a PEM fuel cell power plant with a steam reforming fuel processor, a PSA unit for reformate hydrogen purification, and a VPSA unit for oxygen enrichment.

5   ## DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Figs. 1 - 5

Fig. 1 shows a rotary PSA module 1, which includes a number "N" of
10   adsorbers 3 in adsorber housing body 4. Each adsorber has a first end 5 and a second end 6, with a flow path therebetween contacting a nitrogen-selective adsorbent. The adsorbers are deployed in an axisymmetric array about axis 7 of the adsorber housing body. The housing body 4 is in relative rotary motion about axis 7 with first and second functional bodies 8 and 9, being engaged across a first
15   valve face 10 with the first functional body 8 to which feed gas mixture is supplied and from which the heavy product is withdrawn, and across a second valve face 11 with the second functional body 9 from which the light product is withdrawn.

In preferred embodiments as particularly depicted in Figs. 1 - 5, the
20   adsorber housing 4 rotates and shall henceforth be referred to as the adsorber rotor 4, while the first and second functional bodies are stationary and together constitute a stator assembly 12 of the module. The first functional body shall henceforth be referred to as the first valve stator 8, and the second functional body shall henceforth be referred to as the second valve stator 9.

25

In the embodiment shown in Figs. 1 - 5, the flow path through the adsorbers is parallel to axis 7, so that the flow direction is axial, while the first and second valve faces are shown as flat annular discs normal to axis 7. However, more generally the flow direction in the adsorbers may be axial or
30   radial, and the first and second valve faces may be any figure of revolution centred on axis 7. The steps of the process and the functional compartments to

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be defined will be in the same angular relationship regardless of a radial or axial flow direction in the adsorbers.

Figs. 2 - 5 are cross sections of module 1 in the planes defined by arrows
12 - 13, 14 - 15, and 16 - 17.   Arrow 20 in each section shows the direction of rotation of the rotor 4.   Fig. 2 shows section 12 - 13 across Fig.1, which crosses the adsorber rotor.   In this example, "N" = 72.   The adsorbers 3 are mounted between outer wall 21 and inner wall 22 of adsorber wheel 208.   Each adsorber comprises a rectangular flat pack 3 of adsorbent sheets 23, with spacers 24
between the sheets to define flow channels here in the axial direction.   Separators 25 are provided between the adsorbers to fill void space and prevent leakage between the adsorbers.   In other configurations, the adsorbent sheets may be formed in curved packs or spiral rolls.

Satisfactory adsorbent sheets have been made by coating a slurry of zeolite crystals with binder constituents onto the reinforcement material, with successful examples including nonwoven fibreglass scrims, woven metal fabrics, and expanded aluminum foils. The adsorbent sheets comprise a reinforcement material, in preferred embodiments glass fibre, metal foil or wire mesh, to which the
adsorbent material is attached with a suitable binder. For applications such as hydrogen purification, some or all of the adsorbent material may be provided as carbon fibers, in woven or nonwoven form to serve as its own reinforcement material.   Spacers are provided by printing or embossing the adsorbent sheet with a raised pattern, or by placing a fabricated spacer between adjacent pairs of
adsorbent sheets. Alternative satisfactory spacers have been provided as woven metal screens, non-woven fibreglass scrims, and metal foils with etched flow channels in a photolithographic pattern.

Typical experimental sheet thicknesses have been 150 microns, with spacer
heights in the range of 100 to 150 microns, and adsorber flow channel length approximately 20 cm. Using X type zeolites, excellent performance has been

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achieved in oxygen separation from air and hydrogen purification from reformate at PSA cycle frequencies in the range of 30 to 150 cycles per minute.

As shown in Fig. 1, the adsorbers 3 comprise a plurality of distinct zones between the first end 5 and the second end 6 of the flow channels, here shown as three zones respectively a first zone 26 adjacent the first end 5, a second zone 27 in the middle of the adsorbers, and a third zone 28 adjacent the second end 6. The first zone typically contains an adsorbent or dessicant selected for removing very strongly adsorbed components of the feed gas mixture, such as water or methanol vapour, and some carbon dioxide. The second zone contains an adsorbent typically selected for bulk separation of impurities at relatively high concentration, and the third zone contains an adsorbent typically selected for polishing removal of impurities at relatively low concentration.

In embodiments with three zones, the first zone may be the first 10% to 20% of the flow channel length from the first end, the second zone may be the next roughly 40% to 50% of the channel length, and the third zone the remainder. In embodiments with only two adsorber zones, the first zone may be the first 10% to 30% of the flow channel length from the first end, and the second zone the remainder. The zones may be formed by coating the different adsorbents onto the adsorbent support sheet material in bands of the same width as the flow channel length of the corresponding zone. The adsorbent material composition may change abruptly at the zone boundary, or may be blended smoothly across the boundary. Particularly in the first zone of the adsorber, the adsorbent must be compatible with significant concentrations of water vapour.

Fig. 3 shows the porting of rotor 4 in the first and second valve faces respectively in the planes defined by arrows 14 - 15, and 16 - 17. An adsorber port 30 provides fluid communication directly from the first or second end of each adsorber to respectively the first or second valve face.

- 20 -

Figs. 4A and 4B show the first stator valve face 100 of the first stator 8 in the first valve face 10, in the plane defined by arrows 14 – 15. Fluid connections are shown to a feed compressor 101 inducting feed gas from inlet filter 102, and to an exhauster 103 delivering second product to a second product delivery conduit 104.

5   Compressor 101 and exhauster 103 are shown coupled to a drive motor 105.

Arrow 20 indicates the direction of rotation by the adsorber rotor. In the annular valve face between circumferential seals 106 and 107, the open area of first stator valve face 100 ported to the feed and exhaust compartments is indicated by

10   clear angular segments 111 - 116 corresponding to the first functional ports communicating directly to functional compartments identified by the same reference numerals 111 - 116. The substantially closed area of valve face 100 between functional compartments is indicated by hatched sectors 118 and 119 which are slippers with zero clearance, or preferably a narrow clearance to reduce friction and

15   wear without excessive leakage. Typical closed sector 118 provides a transition for an adsorber, between being open to compartment 114 and open to compartment 115. Gradual opening is provided by a tapering clearance channel between the slipper and the sealing face, so as to achieve gentle pressure equalization of an adsorber being opened to a new compartment. Much wider closed sectors (e.g. 119) are provided

20   to substantially close flow to or from one end of the adsorbers when pressurization or blowdown is being performed from the other end.

The feed compressor provides feed gas to feed pressurization compartments 111 and 112, and to feed production compartment 113. Compartments 111 and 112

25   have succcessively increasing working pressures, while compartment 113 is at the higher working pressure of the PSA cycle. Compressor 101 may thus be a multistage or split stream compressor system delivering the appropriate volume of feed flow to each compartment so as to achieve the pressurization of adsorbers through the intermediate pressure levels of compartments 111 and 112, and then the

30   final pressurization and production through compartment 113. A split stream compressor system may be provided in series as a multistage compressor with interstage delivery ports; or as a plurality of compressors or compression cylinders

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in parallel, each delivering feed air to the working pressure of a compartment 111 to
113. Alternatively, compressor 101 may deliver all the feed gas to the higher
pressure, with throttling of some of that gas to and 112 at their respective
intermediate pressures.

5

Similarly, exhauster 103 exhausts heavy product gas from countercurrent
blowdown compartments 114 and 115 at the successively decreasing working
pressures of those compartments, and finally from exhaust compartment 116 which
is at the lower pressure of the cycle. Similarly to compressor 101, exhauster 103

10   may be provided as a multistage or split stream machine, with stages in series or in
parallel to accept each flow at the appropriate intermediate pressure descending to the
lower pressure.

In the example embodiment of Fig. 4A, the lower pressure is ambient

15   pressure, so exhaust compartment 116 communicates directly to heavy product
delivery conduit 104. Exhauster 103 thus is an expander which provides pressure
letdown with energy recovery to assist motor 105 from the countercurrrent blowdown
compartments 114 and 115. For simplicity, exhauster 103 may be replaced by
throttling orifices as countercurrent blowdown pressure letdown means from

20   compartments 114 and 115.

In some preferred embodiments, the lower pressure of the PSA cycle is
subatmospheric. Exhauster 103 is then provided as a vacuum pump, as shown in Fig.
4B. Again, the vacuum pump may be multistage or split stream, with separate

25   stages in series or in parallel, to accept countercurrent blowdown streams exiting their
compartments at working pressures greater than the lower pressure which is the
deepest vacuum pressure. In Fig. 4B, the early countercurrent blowdown stream
from compartment 114 is released at ambient pressure directly to heavy product
delivery conduit 104. If for simplicity a single stage vacuum pump were used, the

30   countercurrent blowdown stream from compartment 115 would be throttled down to
the lower pressure over an orifice to join the stream from compartment 116 at the
inlet of the vacuum pump.

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If the feed gas is provided at an elevated pressure at least equal to the higher pressure of the PSA cycle, as may conveniently be the case of a hydrogen PSA operating with e.g. methanol reformate feed, compressor 101 would be eliminated. To reduce energy losses from irreversible throttling over orifices to supply feed

5   pressurization compartments e.g. 111, the number of feed pressurization stages may be reduced, sot that adsorber repressurization is largely achieved by product pressurization, by backfill from light reflux steps. Alternatively, compressor 101 may be replaced in part by an expander which expands feed gas to a feed pressurization compartment e.g. 111 from the feed supply pressure of the higher

10   pressure to the intermediate pressure of that compartment, so as to recover energy for driving a vacuum pump 103 which reduces the lower pressure below ambient pressure so as to enhance the PSA process performance.

Figs. 5A and 5B shows the second stator valve face, at section 16 – 17 of Fig.

15   1. Open ports of the valve face are second valve function ports communicating directly to a light product delivery compartment 121; a number of light reflux exit compartments 122, 123, 124 and 125; and the same number of light reflux return compartments 126, 127, 128 and 129 within the second stator. The second valve function ports are in the annular ring defined by circumferential seals 131 and 132.

20   Each pair of light reflux exit and return compartments provides a stage of light reflux pressure letdown, respectively for the PSA process functions of supply to backfill, full or partial pressure equalization, and cocurrent blowdown to purge.

Illustrating the option of light reflux pressure letdown with energy recovery,

25   a split stream light reflux expander 140 is shown in Figs. 1 and 5A to provide pressure let-down of four light reflux stages with energy recovery. The light reflux expander provides pressure let-down for each of four light reflux stages, respectively between light reflux exit and return compartments 122 and 129, 123 and 128, 124 and 127, and 125 and 126 as illustrated. The light reflux expander 140 may power a light product

30   booster compressor 145 by drive shaft 146, which delivers the oxygen enriched light product to oxygen delivery conduit 147 and compressed to a delivery pressure above the higher pressure of the PSA cycle.

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Since the light reflux and light product have approximately the same purity, expander 140 and light product compressor 145 may be hermetically enclosed in a single housing which may conveniently be integrated with the second stator as shown in Fig. 1. This configuration of a "turbocompressor" light product booster without a

5   separate drive motor is advantageous, as a useful pressure boost of the light product can be achieved without an external motor and corresponding shaft seals, and can also be very compact when designed to operate at very high shaft speeds.

Fig. 5B shows the simpler alternative of using a throttle orifice 150 as the

10   pressure letdown means for each of the light reflux stages.

Turning back to Fig. 1, compressed feed gas is supplied to compartment 113 as indicated by arrow 125, while heavy product is exhausted from compartment 117 as indicated by arrow 126. The rotor is supported by bearing 160 with shaft seal 161

15   on rotor drive shaft 162 in the first stator 8, which is integrally assembled with the first and second valve stators. The adsorber rotor is driven by motor 163 as rotor drive means.

As leakage across outer circumferential seal 131 on the second valve face 11

20   may compromise light product purity, and more importantly may allow ingress of humidity into the second ends of the adsorbers which could deactivate the nitrogen-selective or CO-selective adsorbent, a buffer seal 170 is provided to provide more positive sealing of a buffer chamber 171 between seals 131 and 171. Even though the working pressure in some zones of the second valve face may be subatmospheric

25   (in the case that a vacuum pump is used as exhauster 103), buffer chamber is filled with dry light product gas at a buffer pressure positively above ambient pressure. Hence, minor leakage of light product outward may take place, but humid feed gas may not leak into the buffer chamber. In order to further minimize leakage and to reduce seal frictional torque, buffer seal 171 seals on a sealing face 172 at a much

30   smaller diameter than the diameter of circumferential seal 131. Buffer seal 170 seals between a rotor extension 175 of adsorber rotor 4 and the sealing face 172 on the second valve stator 9, with rotor extension 175 enveloping the rear portion of second

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valve stator 9 to form buffer chamber 171. A stator housing member 180 is provided as structural connection between first valve stator 8 and second valve stator 9.

In the following figures of this disclosure, simplified diagrams will represent
5   the PSA apparatus as described above. These highly simplified diagrams will indicate just a single feed conduit 181 to, and a single heavy product conduit 182 from, the first valve face 10; and the light product delivery conduit 147 and a single representative light reflux stage 184 with pressure let-down means communicating to the second valve face 11. Reference numerals pertaining to PSA units as described
10   above will be unprimed for an oxygen enrichment PSA or VPSA unit, and primed for a hydrogen purification PSA or VPSA unit.

Figs. 6 - 8

15   Figs. 6 – 8 show a fuel cell power plant 200, according to the present invention, comprising a fuel cell 202, a steam reforming fuel processor 204, a hydrogen purification PSA system 205, and an oxygen enrichment PSA or VPSA system 206. The fuel cell comprises an anode channel 208 including an anode gas inlet 210 and an anode gas outlet 212, a cathode channel 214 including a cathode
20   gas inlet 216 and a cathode gas outlet 218, and a PEM electrolyte membrane 220 cooperating with the anode channel 208 and the cathode channel 214 for facilitating ion exchange between the anode channel 208 and the cathode channel 214.

The oxygen PSA or VPSA system 206 extracts oxygen gas from feed air,
25   and comprises a PSA rotary module 1 and a compressor 101 for delivering pressurized feed air to the feed compartments of the rotary module 1. Nitrogen enriched gas as heavy product gas from the blowdown and exhaust compartments of the rotary module 1 is withdrawn by conduit 182, either for discharge directly by atmosphere as in Fig. 6 or to a vacuum pump 103 for discharge as in Fig. 7.
30   The adsorbers 3 of rotary module 1 have a first zone 26 loaded with a suitable dessicant such as alumina gel for removal of water vapour, and a second zone 27 loaded with a nitrogen-selective zeolite. Dry oxygen enriched air as the light

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product gas of VPSA module 1 is delivered by conduit 147 to humidification
chamber 230 and thence by conduit 231 to cathode inlet 216. A portion of the
oxygen reacts with hydrogen ions when electric current is generated, to form water
in the cathode. The cathode exhaust gas now containing a reduced amount of
5   oxygen (but still typically oxygen-enriched well above ambient air composition)
plus water is withdrawn from cathode exit 218 by conduit 232 to separator 233.

In Figs. 6 and 7, a portion of the humid cathode exhaust gas (or water
condensate)is removed from separator 233 by conduit 234, which transfers water
10   and any recycle oxygen back to humidification chamber 230 for recirculation
through cathode channel 214. Any oxygen recirculation through conduit 234 must
be driven by appropriate recirculation pressure boost means, such as a blower or an
ejector.

15   If fuel processor 204 in Figs. 6 and 7 is a partial oxidation or autothermal
reformer, the remaining oxygen (plus any accumulated argon and nitrogen) and the
fuel cell product water are delivered from separator 233 by conduit 235 to the fuel
processor 204. If fuel processor 204 in Figs. 6 and 7 is a steam reforming reactor,
the fuel cell product water as condensate is delivered from separator 233 by conduit
20   235 to the fuel processor 204.   In that event, accumulations of argon and nitrogen
in the cathode channel must be recycled from separator 233 back to the oxygen
PSA unit as shown in Fig. 8 by conduit 236 to the first valve face 10 of PSA
module 1 as a feed pressurization stream at an intermediate pressure below the
higher pressure of the PSA cycle, or else purged to atmosphere.

25

A hydrocarbon fuel is supplied to the fuel processor 204 by a feed pump or
compressor 260, is combined with water from conduit 235, and is vaporized and
preheated in heat exchanger 262. The preheated stream of fuel and steam is then
admitted to reforming catalytic chamber 264. In the example that the fuel is

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methane, the following steam reforming reactions take place,

$$CH_4 + H_2O \rightarrow CO + 3H_2$$
$$CH_4 + 2H_2O \rightarrow CO_2 + 4H_2$$
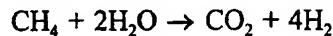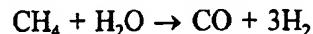
in addition to partial combustion in the case of an autothermal reformer:

$$CH_4 + \tfrac{1}{2}O_2 \rightarrow CO + 2H_2$$
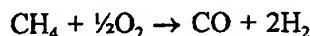
The resulting reformate or "syngas" (dry composition approximately 70% H_2 with roughly equal amounts of CO and CO_2 as major impurities, and unreacted CH_4 and N_2 as minor impurities) is cooled to about 250?C, and then passed to the water gas shift reaction zone 268 for reacting most of the CO with steam to produce more H_2 and CO_2:

$$CO + H_2O \rightarrow CO_2 + H_2$$

The hydrogen rich reformate still contains about 1% to 2% CO after water gas shift, along with substantial amounts of carbon dioxide and water vapour. For high performance and longevity of a PEM fuel cell, it is necessary that CO concentration be reduced well below 100 ppm and preferably below 10 ppm. Consequently, the impure reformate is admitted by conduit 270 to the higher pressure feed port of hydrogen PSA unit 205, including rotary PSA module 1'. The adsorbers 3' of rotary module 1' have a first zone 26' loaded with a suitable dessicant such as alumina gel for removal of water vapour, a second zone 27' loaded with an adsorbent selective for CO removal and at least partial bulk removal of CO_2, and a third zone 28' loaded with an adsorbent suitable for polishing removal of CO and at least partial removal of other impurities such as N_2. The invention provides numerous combinations and variations of suitable adsorbents for the three zones of the hydrogen PSA adsorbers, as recited in our simultaneously filed copending patent application "carbon monoxide removal from fuel cell", the disclosure of which is incorporated herein by this reference thereto.

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Purified hydrogen light product from the hydrogen PSA module 1 is delivered by conduit 147' to anode inlet 216, passed through anode channel 208, and then exhausted from anode exit 218 back to a feed presurization compartment in the first vavle surface 10' of hydrogen PSA module 1', so as to retain hydrogen within the fuel cell anode loop including conduits 147' and 280 and anode channel 208, while using the hydrogen PSA unit to reject impurities that otherwise would accumulate on the anode.

Exhaust second product gas from the hydrogen PSA module contains water vapour, CO_2, and combustible values including H_2, CO and any unreacted fuel from the reformer. This gas is exhausted from valve face 10' by conduit 285 to low pressure burner 290 where this fuel is oxidized completely, preferably over a suitable catalyst to ensure stable combustion of this low BTU gas and to suppress NOx formation. Burner 290 delivers hot products of combustion to heat exchange channel 292, which is in countercurrent thermal contact for heat recovery to reformer reactor zone 264 and preheater zone 262. After cooling in channel 292 and further cooling in heat exchanger 296, the flue gas from burner 290 is discharged to atmosphere by exhaust conduit 294.

Fuel processor 204 is also thermally integrated with a high pressure burner 300, to which a portion of the fuel from fuel pump 260 may be introduced by conduit 301. Compressed air is supplied to burner 300 from feed compressor 101 through conduit 302, heat exchanger 296 (for recuperative heat exchange from exhaust flue gas) and heat exchange channel 304 which is in countercurrent thermal contact for heat recovery from water gas shift reaction zone 268 and reformer reactor zone 264 if the reforming reaction includes partial oxidation for net exothermicity. Hot products of combustion [including nitrogen and unreacted oxygen] from combustion chamber 300 are conveyed by conduit 310 to expander turbine 315, coupled by shaft 316 to compressor 101. The combination of compressor 101 and expander 315 are shown as a free rotor turbocompressor 320, similar to an automotive turbocharger. [Alternatively a drive motor or a generator may be coupled to shaft 316, for starting, power assist, or net energy

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delivery.] In Figs. 6 and 7, a blower 330 driven by motor 332 is provided to boost the inlet pressure to compressor 101, if desired to assist the compression of feed air in normal operation, but preferably only as a starting device to initiate rotation of turbocompressor 320 in which case bypass valve 334 is opened during

5 normal operation after starting.

The still hot gas discharged by expander 315 is discharged by conduit 336 to low pressure burner 290, providing heat and oxygen to support catalytic

10 combustion therein. Supplemental air or oxygen may be provided to low pressure burner 290 if required during starting or any phase of normal operation.

While Fig. 6 shows an embodiment whose lower working pressure is atmospheric, Fig. 7 shows an embodiment with vacuum applied to the oxygen and

15 hydrogen PSA units to improve their performance, perhaps to enable a reduced working pressure of the fuel cell. Vacuum pump 338 receives the second product exhaust gases at subatmospheric pressure from both the oxygen PSA and the hydrogen PSA by respectively conduits 182 and 182', and delivers the combined stream to the catalytic low pressure burner 290 by conduit 285. Vacuum pump 338

20 is provided as a turbocompressor 340 with expander 345 driving pump 338 through shaft 346. Expander 345 is arranged in parallel or series with expander 315 to expand hot gas delivered by conduit 310 from high pressure burner 300.

The combustion turbine embodiments for powering auxiliary compression

25 machinery have the important advantage of using readily available and low cost turbocharger equipment. Fig. 8 shows an alternative embodiment using a rotary internal combustion engine 400 to power the compressor 101 and optional vacuum pump 103 of the oxygen PSA 206 by shaft coupling 405, while itself providing vacuum suction if desired for the hydrogen PSA 205. Engine 400 is fueled at

30 least in part by the hydrogen PSA tail gas, and has a starter motor 410 (or supplemental power output generator 410).

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Engine 400 may be any type of internal combustion engine, but is here shown as a Wankel engine. Working chambers 412 are defined between rotor 414 and casing 415. The rotor is coupled to drive shaft 405 by internal gear 416. An intake port 421, exhaust port 422 and spark plugs 423 are provided in casing 415.

5   A water cooling jacket 425 is provided. The engine has an air filter 426 delivering air to carburetor 427, and to intake port 422. The carburetor mixes the air with hydrogen PSA exhaust gas delivered by exhaust conduit 182' to carburetor 427.

Fig. 8 shows details of an illustrative water management system. Product

10   water of fuel cell 202 is captured in separator 233 which has a cooling coil 430, and is delivered to liquid water manifold 432. A portion of the water is delivered from manifold 432 to pump 435, and thence by flow control 436 to the oxygen humidification chamber 230 and by flow control 437 to engine cooling jacket 425. Hot water from the engine cooling jacket is flash evaporated and delivered through

15   depressurization orifice 485 and conduit 486 to methanol reforming reactor catalyst zone 264, which in turn is in heat exchange contact with the engine exhaust in channel 440. Engine exhaust is delivered from exhaust port 422 to channel 440 for exhaust heat recovery to the endothermic methanol vapour phase reforming reaction in reactor zone 264, and then through emission control after-treatment catalyst 443

20   and exhaust pipe 444 to atmosphere.

Reformate hydrogen is delivered from reactor zone 264 by conduit 450 to feed hydrogen PSA unit 205. A portion of the reformate may be diverted to carbuertor 427 from conduit 450 by flow control 452 as supplemental fuel for

25   engine 400.

A portion of the water condensate in water manifold 434 is delivered by pump 460 to liquid fuel mixing chamber 465, which also receives liquid methanol fuel delivered by fuel pump 260. The flow rates of pumps 260 and 460 are

30   adjusted to achieve a desired concentration ratio of the water/methanol mixture exiting the mixing chamber 465 by conduit 466 delivering this mixture as fuel cell stack coolant circulated through cooling passage 468 through the fuel cell stack

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202.   The coolant pressure is maintained high enough to maintain it in the liquid phase within the cooling passage. A portion of the water/methanol mixture coolant exiting cooling passage 468 is flash evaporated in separator 474 by depressurization valve 475 to approximately the working pressure of reforming reactor zone 264, and the resulting vapour mixture is delivered by conduit 480 to the reforming reactor catalytic zone 264. The balance of the water/methanol mixture coolant is repressurized and recirculated by pump 470 through cooling radiator 471 to reject fuel cell stack heat that has not been recovered to vaporize the water and methanol reactants.

10

Fig. 1
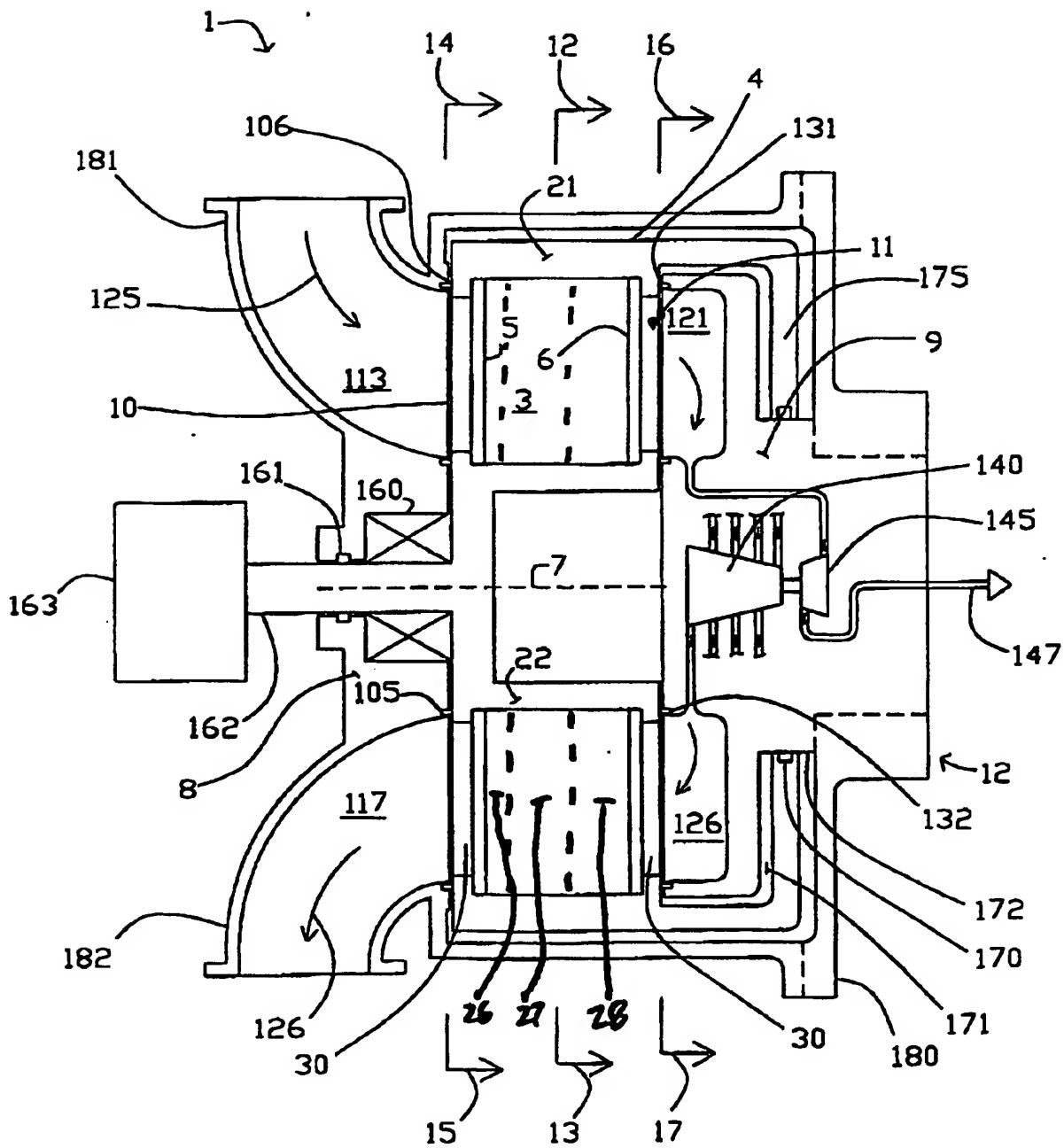
Fig. 2
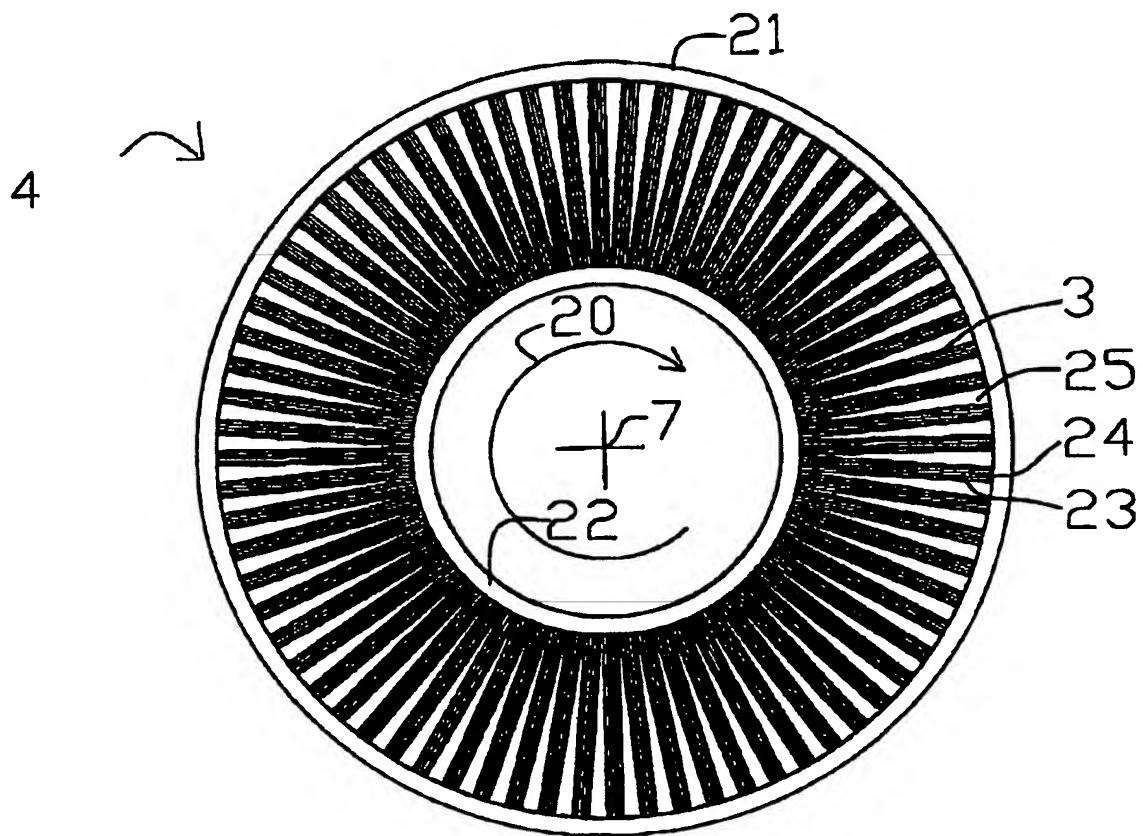
Fig. 3
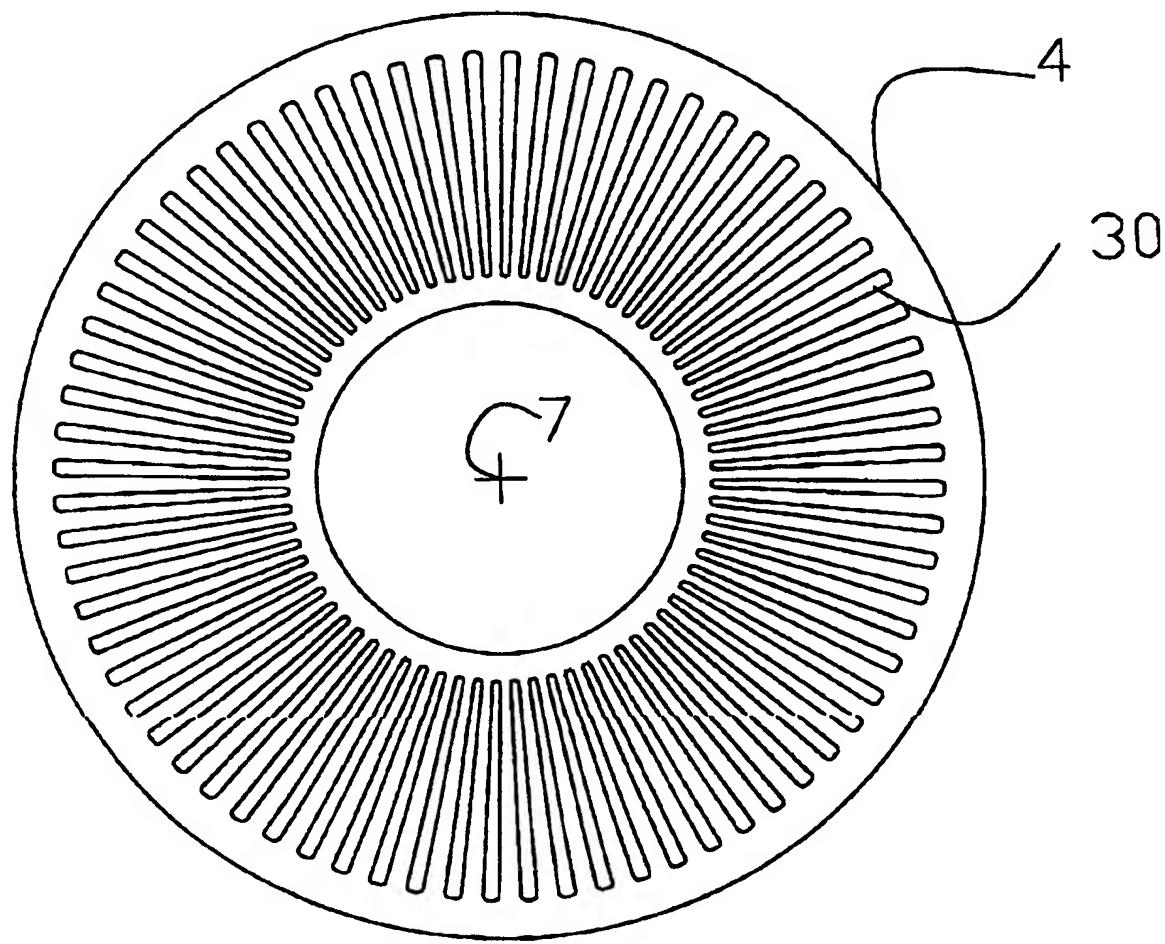
Fig. 4A
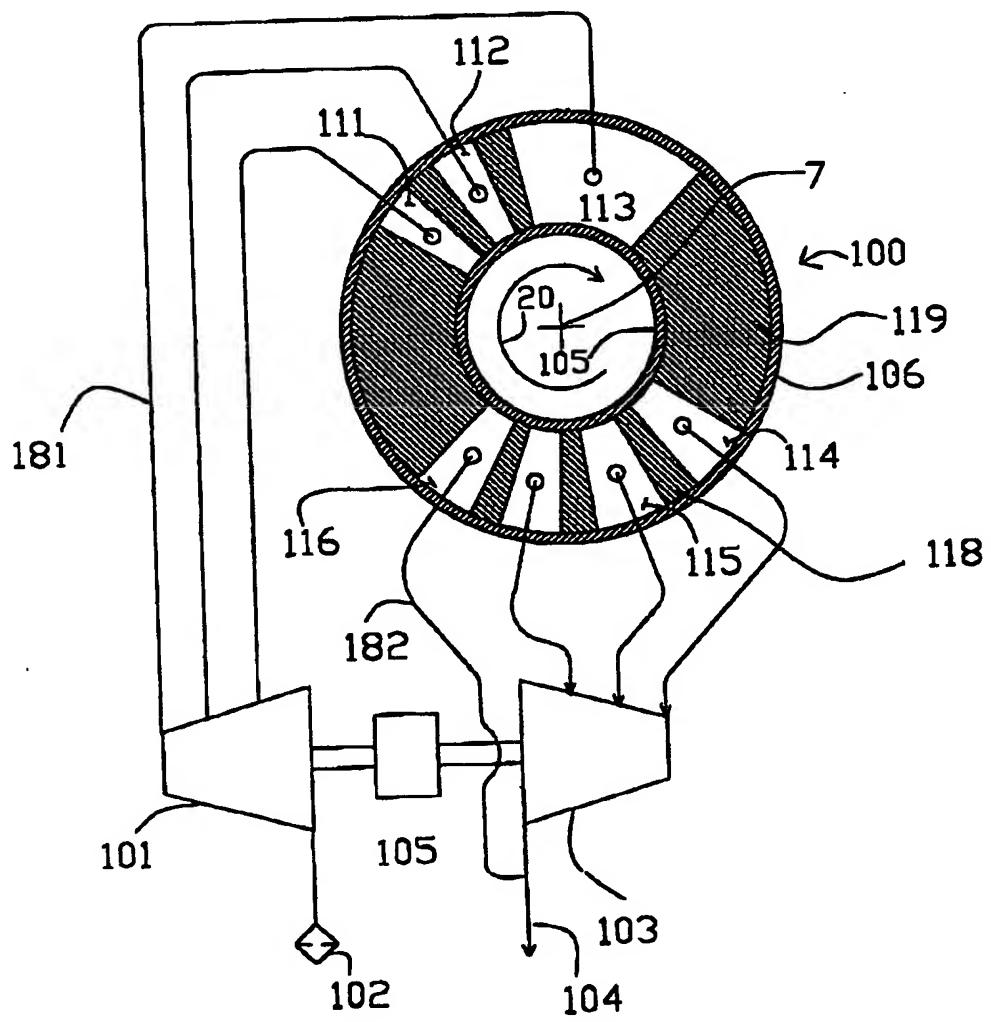
Fig. 4B

Fig. 5A

Fig. 5B

FIG· 6

FIG. 7

Fig. 8